ORGANIC LETTERS

2012
Vol. 14, No. 17
4606–4609

A General Method for Suzuki–Miyaura Coupling Reactions Using Lithium Triisopropyl Borates

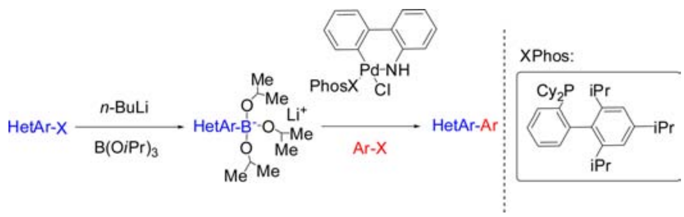
Matthias A. Oberli and Stephen L. Buchwald*

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

sbuchwal@mit.edu

Received July 25, 2012

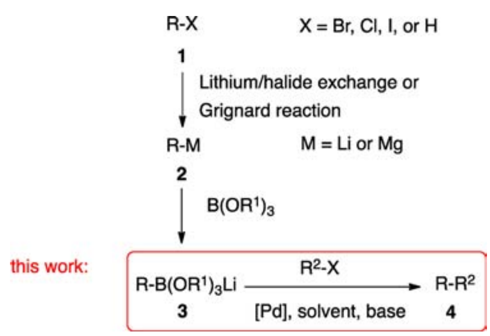
ABSTRACT



Conditions for the Suzuki–Miyaura coupling of lithium triisopropyl borates are reported, as well as a procedure for a one-pot lithiation, borylation, and subsequent Suzuki–Miyaura coupling of various heterocycles with aryl halides. These borate species are much more stable toward protodeboronation than the corresponding boronic acids and can conveniently be stored on benchtop at room temperature.

The Suzuki–Miyaura cross-coupling (SMC) reaction has become an indispensible tool for the preparation of a wide variety of organic molecules and materials.[1,2] Key to the success of this reaction is the inherent compatibility of organoboron compounds with many functional groups,[3] their low toxicity, and the fact that many organoboronic acids are commercially available. However, under the most commonly used SMC conditions, many organoboronic acids, especially five-membered heterocyclic boronic acids, are prone to decomposition via protodeboronation and other processes.[4] To address these issues, both improved catalyst systems[5] and protected or masked boronate substrates[6] have been developed, allowing for the cross-coupling of inherently unstable boronic acids such as five-membered heterocycles[7] and polyfluorophenyl boronic acids.[5a]

Scheme 1. Preparation and Use of Lithium Triisopropyl Borates **3** as Nucleophiles for Suzuki–Miyaura Reactions



(1) (a) Miyaura, N.; Suzuki, A. *J. Chem. Soc., Chem. Commun.* **1979**, 866–867. (b) Miyaura, N.; Yamada, K.; Suzuki, A. *Tetrahedron Lett.* **1979**, *20*, 3437–3440. (c) Miyaura, N.; Yanagi, T.; Suzuki, A. *Synth. Commun.* **1981**, *11*, 513–519.

(2) For selected reviews about the Suzuki–Miyaura cross-coupling, see: (a) Fleckenstein, C. A.; Plenio, H. *Chem. Soc. Rev.* **2010**, *39*, 694–711. (b) Martin, R.; Buchwald, S. L. *Acc. Chem. Res.* **2008**, *41*, 1461–1473. (c) Blleina, F.; Carpita, A.; Rossi, R. *Synthesis* **2004**, 2419–2440. (d) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457–2483.

(3) Molander, G. A.; Figueroa, R. *Aldrichimica Acta* **2005**, *38*, 49–56.

(4) (a) Kuivila, H. G.; Reuwer, J. F.; Mangravite, J. A. *Can. J. Chem.* **1963**, *41*, 3081–3090. (b) Kuivila, H. G.; Reuwer, J. F.; Mangravite, J. A. *J. Am. Chem. Soc.* **1964**, *86*, 2666–2670.

(5) (a) Kinzel, T.; Zhang, Y.; Buchwald, S. L. *J. Am. Chem. Soc.* **2010**, *132*, 14073–14075. (b) Yang, D. X.; Colleti, S. L.; Wu, K.; Song, M.; Li, G. Y.; Shen, H. C. *Org. Lett.* **2009**, *11*, 381–384. (c) Wuttke, E.; Nägele, B.; Weibert, B.; Kessler, F. *Organometallics* **2011**, *30*, 6270–6282.

(6) (a) Billingsley, K. L.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 4695–4698. (b) Yamamoto, Y.; Takizawa, M.; Yu, X.-Q.; Miyaura, N. *Angew. Chem., Int. Ed.* **2008**, *47*, 928–931. (c) Noguchi, H.; Shioda, T.; Chou, C.-M.; Suginome, M. *Org. Lett.* **2008**, *10*, 377–380. (d) Hodgson, P. B.; Salingue, F. H. *Tetrahedron Lett.* **2004**, *45*, 685–687. (e) Gravel, M.; Thomson, K. A.; Zak, M.; Bérubé, C.; Hall, D. G. *J. Org. Chem.* **2002**, *67*, 3–15.

10.1021/ol302063g
Published on Web 08/15/2012

Lithium triisopropyl borates (LTB) are often accessed as intermediates in the syntheses of commonly used masked boronates such as the organotrifluoroborates[8] and *N*-methyliminodiacetic acid (MIDA) boronates (Scheme 1).[9] Specifically lithium triisopropyl 2-pyridinylborates have been employed directly as nucleophiles for SCM reactions.[6a] However, the coupling of other LTB nucleophiles, particularly those derived from heterocycles that form unstable boronic acids, has been largely unexplored. Herein, we report the use of lithium triisopropyl borates as nucleophiles in SCM reactions for a wide range of heterocycles.

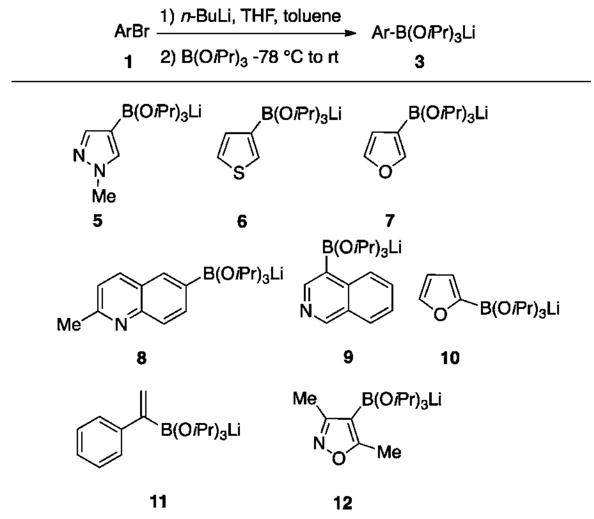
Lithium triisopropyl borates (LTB) **3** are readily prepared via a one-pot procedure.[6d] For the borates depicted in Scheme 2, lithiation at −78 °C was followed by the addition of triisopropyl borate, after which the solution was gradually warmed to room temperature. The solvent was then removed, and the resulting LTB was dried under vacuum at 80 °C. The crude borate salt, still containing lithium bromide, was directly used in SMC reactions without any further purification based on a 100% yield.[10]

Using this procedure, lithium triisopropyl borates **5**−**12** were synthesized and subsequently used as nucleophiles in SMC reactions with various aryl and heteroaryl electrophiles. We began by evaluating the use of LTBs under conditions previously reported for the SMC using a diphenyl phosphine oxide ligand.[6a] While these couplings were successful, we found that by using XPhos precatalyst **13** we could obtain higher yields of coupled products under milder reaction conditions and in shorter reaction times (Scheme 3). The use of precatalyst **13** was crucial in that it rapidly generates the catalytically active Pd(0)L_1 catalyst at the low reaction temperature (40 °C) required for the efficient coupling of these sensitive borates. The reactions were run with a 3 mol % catalyst loading in a 1:2 THF/aqueous 0.5 M K_3PO_4 solution. Decreasing the loading of **13** from 3 to 1 mol % resulted in a slightly lower yield (**14b**, 96% vs **14c**, 84%).

Aryl bromides, chlorides, and triflates were all competent electrophiles and could be coupled with good to excellent yields. Significantly, the mild reaction conditions allowed for the coupling of (L)-4-bromophenylalanine without any erosion in enantioselectivity **24**.

We were next interested in evaluating the stability of these unpurified heteroaryl triisopropyl borates if not used immediately for an SMC and found that borates **5**−**12** were remarkably robust. When used in an SMC reaction, these borates reacted to provide products in comparable yields even after being stored at room temperature for a month in a closed vial under air. In fact, the use of aryl borates **5**, **7**, and **10** gave comparable yields in SCM reactions after storage under air for up to 4 months. In comparison, 2-furanyl boronic acid loses 90% of its activity following storage under air for just 15 days.[9a]

Scheme 2. Synthesis of Lithium Triisopropyl Borates[a]



[a] These were isolated and used in coupling reactions without purification. Reaction conditions: ArBr (3.16 mmol), THF (3 mL), toluene (12 mL), *n*-BuLi (1.4 mL, 2.5 M in hexanes, 3.48 mmol, 1.1 equiv), B(O*i*Pr)$_3$ (0.75 mL, 3.48 mmol, 1.1 equiv), −78 °C to rt, 8 h.

We hypothesize that the bulky isopropyl groups in the LTB protect the borate against protodeboronation. Since no reaction was observed with LTB under anhydrous SMC reaction conditions, we also presume that hydrolysis of the LTBs to their corresponding boronic acids is required for fast and efficient transmetalation. However, an advantage of using the boronate complex as a nucleophile is that the reaction occurs in a THF/water mixture as solvent with no additional base added, as upon hydrolysis, basic isopropylate is released. The pH value of a typical reaction mixture in THF with water as cosolvent is between 12 and 13. Thus, the use of LTB nucleophiles allows for SMC reaction with base-sensitive substrates such as nitro aromatics, methyl esters, or oxazoles (Scheme 4).[11]

We next sought to combine the lithiation, borylation, and SMC reaction into a one-pot procedure. Previously, we showed that an analogous one-pot sequence could be successfully applied to flow conditions.[12] To this end, the aqueous base was directly added to the crude solution of LTB at −78 °C, followed by the aryl halide, precatalyst **13**,

(7) (a) Kabri, Y.; Gellis, A.; Vanelle, P. *Eur. J. Org. Chem.* **2009**, *24*, 4059–4066. (b) Gill, G. S.; Grobelny, D. W.; Chaplin, J. H.; Flynn, B. L. *J. Org. Chem.* **2008**, *73*, 1131–1134. (c) Billingsley, K. L.; Buchwald, S. L. *J. Am. Chem. Soc.* **2007**, *129*, 3358–3366. (d) Billingsley, K. L.; Anderson, K. W.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 3484–3488. (e) Tyrell, E.; Brookes, P. *Synthesis* **2004**, 469–483. (f) Fleckenstein, C. A.; Plenio, H. *J. Org. Chem.* **2008**, *73*, 3236–3244. (g) Li, J.-H.; Zhu, Q.-M.; Xie, Y.-X. *Tetrahedron* **2006**, *62*, 10888–10895.

(8) (a) Molander, G. A.; Ellis, N. M. *Acc. Chem. Res.* **2007**, *40*, 275–286. (b) Molander, G. A.; Canturk, B. *Angew. Chem., Int. Ed.* **2009**, *48*, 9240–9261. (c) Stefani, H.; Cella, R.; Vieira, A. *Tetrahedron* **2007**, *63*, 3623–3658.

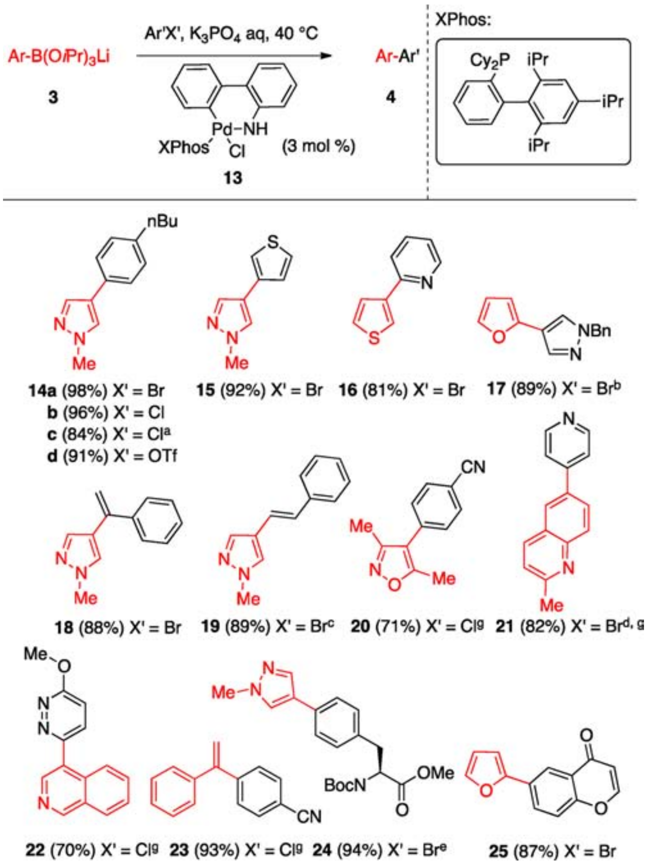
(9) (a) Knapp, D. M.; Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2009**, *131*, 6961–6963. (b) Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2007**, *129*, 6716–6717.

(10) It should be noted that, while 6-bromo-2-methylquinoline was effectively transformed into **8**, during attempts to transform 4-bromoquinoline and *N*-methylbenzimidazole into their corresponding LTBs, the addition of an *n*-butyl group to the 2-position was observed.

(11) The Suzuki−Miyaura reactions described in this paper worked, in general, in THF with water as cosolvent. For some heterocyclic substrate combinations, however, the use of THF combined with aqueous potassium phosphate solution afforded higher yields.

(12) Shu, W.; Pellegatti, L.; Oberli, M. A.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2011**, *50*, 10665–10669.

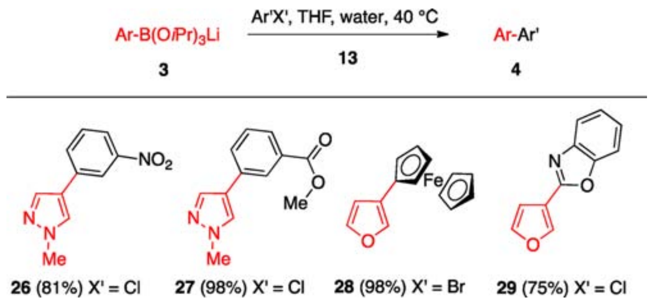
Scheme 3. Heteroaryl Triisopropyl Borates as Nucleophile in SMC Reactions



[a] 1% precatalyst **13** was used. [b] 87% yield after storing lithium triisopropyl 2-furanyl borate for 4 months in a closed vial on a benchtop. [c] 6% *Z*-isomer was obtained that corresponds to the same *E*/*Z* ratio as in the starting material. [d] 4-Bromopyridine was used as HCl salt. [e] Without racemization. [f] Reaction conditions: ArX (0.25 mmol, 1.0 equiv), **3** (0.375 to 0.75 mmol, 1.5 to 3.0 equiv), **13** (3 mol %), THF (0.5 mL), and K_3PO_4 aq (0.5 M, 1.0 mL), 2 h, 40 °C. Isolated yields are the average of two runs. [g] 3 equiv of **3** were used.

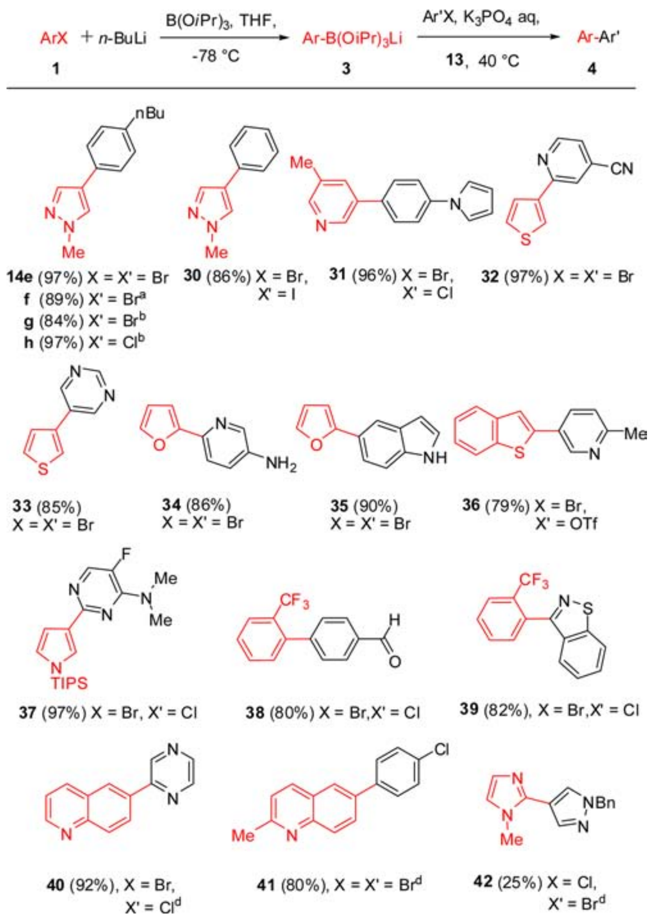
and stirring the SMC at 40 °C for 2 h. We found that product formation occurred in yields similar to those of SMC reactions conducted with isolated LTB (Scheme 5). We investigated conducting the SMC at a lower catalyst loading (1 mol %) and found that, particularly for aryl bromide electrophiles, the products were obtained in slightly lower yields (**14e** to **14g**). In the case of aryl chloride electrophiles, however, 1 mol % of precatalyst **13** was sufficient (**14h**). Under the optimized conditions, a broad scope of heterocyclic aryl halides were successful SMC substrates. For the electrophilic coupling partner, pyridines (**32**, **34**, and **36**), pyrimidines (**33** and **37**), 1*H*-indoles (**35**), aromatic aldehydes (**42**), 3-chloro-1,2-benzisothiazole (**39**), and pyrazines (**40**) were all good substrates. Notably, aryl bromides could also be selectively coupled in the presence of chlorides (**41**). Nucleophiles bearing acidic protons were incompatible and required the use of protecting groups. In particular, a TIPS-protected pyrrole and an SEM-protected pyrazole worked well in the lithiation/borylation sequence to provide products **37** (Scheme 5) and **45** (Scheme 6) in good yields.

Scheme 4. SMC Reaction in THF/Water Enables the Coupling of Base Sensitive Substrates[a]



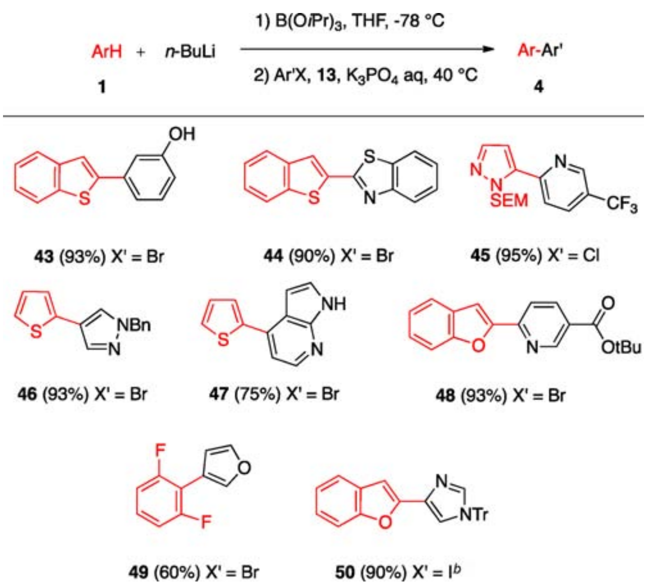
[a] Reaction conditions: **3** (0.375 mmol, 1.5 equiv), Ar′X′ (0.25 mmol, 1.0 equiv), **13** (3 mol %), THF (0.5 mL), water (1.0 mL). Isolated yields based on two runs.

Scheme 5. One Pot Lithium−Halogen Exchange, Borylation, and SCM Reaction



[a] 2% precatalyst **13** was used. [b] 1% precatalyst **13** was used. [c] Reaction conditions: ArX (0.375 mmol, 1.5 equiv), THF (0.5 mL), *n*-BuLi (2.5 M in hexanes, 0.41 mmol, 1.7 equiv), B(O*i*Pr)$_3$ (0.41 mmol, 1.7 equiv), −78 °C, 1 h, K_3PO_4 aq (0.5 M, 1.0 mL), ArX (0.25 mmol, 1.0 equiv), **13** (3 mol %), 2 h, 40 °C. Isolated yields are the average of two runs. [d] 3 equiv of ArX were used.

Scheme 6. One Pot Lithium–Halogen Exchange, Borylation, and SCM Reaction of Heteroarenes[a]



[a] Reaction conditions: ArX (0.75 mmol, 3.0 equiv), THF (1.0 mL), *n*-BuLi (2.5 M in hexanes, 0.83 mmol, 3.3 equiv), B(O*i*Pr)$_3$ (0.83 mmol, 3.3 equiv), −78 °C, 1 h, K_3PO_4 aq (0.5 M, 2.0 mL), ArX (0.25 mmol, 1.0 equiv), **13** (3 mol %), 2 h, 40 °C. Isolated yields are the average of two runs. [b] The reaction was run for 5 h instead of 2 h.

The use of Boc or benzyl protection groups, however, resulted in decomposition and/or protecting-group cleavage. While methyl-imidazole only gave a trace amount of coupling product, a trityl-protected imidazole electrophile resulted in good yields of **50**; the use of an *N*-methyl-1*H*-imidazole as the LTB resulted in low yields of coupled product **42**.

Subsequently, we evaluated the lithiation/borylation/SMC reaction sequence using nonhalogenated heterocycles as LTB precursors via initial *ortho*-lithiation. In this sequence, thiophene (**46** and **47**), benzothiophene (**43** and **44**), SEM-pyrazole (**45**), benzofuran (**48** and **50**), and 1,5-difluorobenzene (**49**) performed well (Scheme 6). However, furan, in contrast to bromofuran, did not yield the desired product. To achieve full conversion, 3 equiv of the heteroarene were required.

In conclusion, we have demonstrated that lithium triisopropyl borate salts are convenient and efficient coupling partners for Suzuki–Miyaura reactions, particularly when a sensitive heterocyle is required as the boronate component. In addition to providing a general procedure for the synthesis of LTBs and mild conditions for their coupling, we have developed conditions for a one-pot lithiation/borylation/SMC coupling sequence which provides a variety of heterocyclic bioaryl products in good yields. We expect that these triisopropyl boronate salts, which are stable at room temperature under an atmosphere of air, will find widespread use.

Acknowledgment. We thank the Novartis Foundation, formerly Ciba-Geigy Jubilee Foundation, for a postdoctoral fellowship to M.A.O. We thank Dr. Meredeth A. McGowan (Massachusetts Institute of Technology) and Dr. Marcel Alexander Düfert (Massachusetts Institute of Technology) for help with this manuscript.

Supporting Information Available. Experimental procedures along with experimental and spectroscopic data for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare the following competing financial interest(s): MIT has patents on XPhos from which S.L.B. receives royalty payments.